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Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model

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ABSTRACT

Combined and separate impact of climate and land use change on the future river runoff was assessed in the eastern Baltic Sea region by using the SWAT (The Soil and Water Assessment Tool) hydrological model. SWAT was applied to assess how plausible changes in climate and land use may affect the river hydrology by the end of the century. The model was calibrated and validated for a period from 1970 to 2010 (41 years) using daily river runoff data. Statistical and visual analysis of the achieved model presented adequate fit to the observed data allowing the reproduction of the current hydrological conditions of the basins for future analysis. The following conclusions from the study were made: 1) a strong linear correlation between forest cover change and annual river flow change was found; 2) the impact of land use change on runoff is important on an annual scale; 3) the scale of a basin is not important on the hydrological response to forest cover change; 4) the combined effect of land use and climate change was found to be non-additive. Findings of this study would help policy makers, to improve land and water management decisions and in formulating strategies to harness the positive impacts of possible overall increase in river runoff in the north-eastern Baltic Sea region.

1. Introduction

The statistical distribution of weather patterns is changing. Changes in air temperature and precipitation influence the hydrologic cycle and, moreover, the water resources. Climate change is caused by a possible combination of natural processes and human activity, although the extent of anthropogenic activities is uncertain. According to the intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, the global linear trend (1906–2005) for the annual near surface mean temperature is an increase of 0.74 °C per decade (IPCC, 2007). Furthermore, according to Tietäväinen et al. (2010) the rate of warming has tripled during the last 50 year (up to 0.30C per decade) in the Northern part of the Baltic Sea (Finland). The quality of the data for trend analysis in the first part of the 20-th century is considered low, and the credibility of the data in the second half can be considered as medium (Hartmann et al., 2013). This uncertainty is carried to future predictions, since this data is used as base to drive climate models.

The trends in runoff are influenced by changes in precipitation and temperature, where latter seems to have a stronger impact (The BACC II Author Team, 2015). Jaagus (2006) analyzed trends in the time series of air temperature and precipitation in Estonia during 1951–2000. There has been a statistically significant increase in air temperature during the cold period. In precipitation, increasing trends are present from October until March, and also in June. The duration of snow cover has decreased in Estonia 17–20 and 21–36 days, on the inland and coast, respectively. An increase in winter discharge has been detected in the Baltic Sea sub-basins. This is due to the higher temperatures, causing earlier snowmelt (BACC Author Team, 2008). It is evident from the above that in the eastern Baltic Sea region, the climate is changing.

Hydrological models are one of the tools to assess the possible changes in the future hydrology and water resources. Some of the widely used in the Baltic Sea region are the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2005), HBV (Bergström and Forsman, 1973; Lindström et al., 1997), Hydrological Predictions for the Environment (HYPE) (Lindström et al., 2010) and Hydrological Simulation Program Fortran (HSPF) (Bicknell et al., 1997). Hydrological models in these studies take into account the climate change impact on water quantity (Kjellström and Lind, 2009; Kriaučiūnienė et al., 2008; Latkovska et al., 2012; Øygarden et al., 2014; Tamm et al., 2015) or quality (Arheimer et al., 2012; Donnelly et al., 2011; Rankinen et al., 2016). However, there are no regional studies about the sole impact of land use change nor combined impact of climate and land-use change on future water resources in the eastern Baltic Sea region. The closest study in this topic has been carried out in the Narew basin, located in the North-East of Poland (Piniewski et al., 2014).

General Circulation Models (GCMs) are one of the basis of future

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climate studies, however, they have a coarse resolution (Flato et al., 2013). Stone (2003) found that in climate change impact studies, the resolution of the climate model plays an important role in estimating water yields in a basin. To overcome this limitation, one of the solutions is to use finer scale regional climate models (RCMs) which are forced by boundary and initial conditions generated by a CGM (Giorgi et al., 1990; Wang et al., 2004). Prein et al. (2016) demonstrated how RCMs clearly added value by improving the representation of spatial precipitation patterns. However, a study by Di Luca et al. (2013) suggests that RCMs may add relatively low additional value to surface temperature. However, they found that the largest potential for added value appears in coastline regions due to different warming of land and water surfaces.

Besides climate change, changes in land use may have a significant effect on hydrology (Wang et al., 2006), and thus, on water resources. At least one-third of the land surface has been modified by humans (Ellis, 2011). This tendency is likely to continue in the future to cope with the growing demand for resources (MEA, 2005). Global forest area has declined over 3% in the period from 1990 to 2015. The conversion of forest land to agricultural use has been the most significant driver for this tendency (Smith et al., 2016). However, in the Baltics, the recent land use change trend has been the opposite. After the Baltic States regained independence from the Soviet Union in 1991, the decrease in the agricultural land use started. This trend can largely be explained by the natural expansion of forest on abandoned agricultural lands and by afforestation, where less fertile lands were planted with trees (Palang et al., 1998). According to FAO (2010) 52% of the total area of Estonia is covered by forest, whereas around 23% is agricultural land. Besides changes in forest and agricultural land, urban land use increase in Estonia has been significant (Roose et al., 2013). Thus the main drivers for land use changes in the Baltics have been both political and economical.

Anthropogenic land-use and land-cover change affects the hydrologic cycle through evapotranspiration and the interception of water. Climate- and land use-induced changes in precipitation and evaporation directly affect the amount of available water, which can theoretically be used for hydropower production or for other uses of water resources.

The extent of climate and land use change effects on water resources vary, being dependent on the region analyzed and scenarios considered (IPCC, 2007). These impact studies should be regionalized in order to achieve a better understanding of the future. This paper proposes to use a semi-distributed hydrological model, the SWAT model (Soil and Water Assessment Tool), to estimate potential impacts of land use (deforestation and afforestation) and climate change on water resources in the West-Estonian river basin district, located in the north-eastern Baltic Sea region. The generated information from climate and land use change scenarios can be useful for relevant policies as guidance for adaption and mitigation measures. The joint effect of climate- and land use change on regional water resources has not been explored to date in the study area.

2. Study area

This study was conducted on the north-eastern Baltic Sea region, in the West-Estonian river basin district. The Baltic Sea drainage basin is about 1,745,000 km^2, which is divided into multiple sub-basins. The Baltic Sea is almost entirely enclosed by land, only connection to the North Sea is through the narrow Straits of Denmark. West-Estonian river basin district flows either to The Gulf of Riga or to the Gulf of Finland, which is the eastern arm of the Baltic Sea.

The West-Estonian river basin district is situated in the west of Estonia and covers an area of approximately 23,500 km^2 (Fig. 1), which is around half of the whole territory of Estonia. The climatic region of the study area can be described as semi-continental (coastal) and continental (inland). The weather is often breezy and humid due to the proximity of the Baltic Sea. The average annual precipitation and actual evaporation in the study area is around 700 and 400 mm, respectively. The average annual temperature in the West-Estonian river basin district was 5.1 °C during the period from 1971 to 2000. The local topography consists of relatively flat ground, with the basin district altitude ranging from 141 m above sea level to 0 m at the coast (drains to the Baltic Sea).

Forests and other wooded areas occupy 52% of the total area of the study basins in the baseline period (Table 1), whereas around 30% is agricultural land and 18% is considered other (urban, wetlands, water bodies etc.). Land use varies in a significant way between study basins. Vihterpalu river basin can be considered highly forested, with almost 60% covered by forest, but only 14% is used for agriculture. From all of the study basins, Keila basin has the largest coverage of agricultural land (around 42%) and just below 40% is categorized as forest.

3. Methods

The procedure for estimating the impacts of possible future climate and land-use change on hydrological behavior, is as follows: (1) parametrization and calibration of the SWAT hydrological model by using current climatic inputs, land-use map and observed river flow; (2) two regional climate models (RCMs) are applied (Luhamaa et al., 2014) and bias corrected against observed climate; (3) land-use change scenarios are generated for the end of the 21th century; (4) future scenarios are generated, based on the combinations of changing climate and land use; (5) the modelling results of the current and the future period are compared with the interquartile range. In the interquartile range, the extreme values (outliers) are excluded.

3.1. Hydrological model SWAT

The hydrological model SWAT is a widely used semi-physically based and a semi-distributed model that can simulate long term runoff and water quality. SWAT has been used in various water quality and quantity studies (Easton et al., 2010; Gassman et al., 2007). In SWAT, a basin can be partitioned into subbasins, and then further into combinations of unique soil, land use and management characteristics also known as hydrological response units (HRU) which are linked to the river network. It is assumed that HRUs are non-spatially distributed. Rainfall and evaporation is calculated for each HRU. In this study, thresholds for defining HRUs were set at 10% for soil and 10% for land use. Potential evapotranspiration was estimated by using the Hargreaves method (Hargreaves and Samani, 1982), for surface runoff calculation, the modified USDA Soil Conversion Service (SCS) curve number method was used.

Observed runoff data was used to calibrate the SWAT model by the software SWAT-CUP, using the SUFI-2 (Sequential Uncertainty Fitting Procedure Version 2) algorithm (Abbaspour, 2008). River runoff from all the study basins was calibrated and validated against daily measured data from 1970 to 2010 (a 41 year continuous period). Calibration was made with observed data from 1970 to 1997 and validation with observed data from 1998 to 2010. Two-year data (1968–1969) was set as a warm-up period.

The goodness of fit was evaluated qualitatively (visually) and quantitatively with the widely used Nash-Sutcliffe coefficient of efficiency (NSE, Nash and Sutcliffe, 1970), percent bias (PBIAS) and Kling-Gupta Efficiency (KGE, Gupta et al., 2009). Using an excessively over-or underestimating hydrological model for future studies (investigating possible changes in water resources), may lead to wrong conclusions. Thus, an acceptable PBIAS value in this study was set to 10% for daily streamflow and NSE/KGE values should exceed 0.65 to be considered satisfactory.

3.2. Climate scenarios

Regional scenarios of future climate are needed in order to assess future climate change impact on water resources with a hydrological

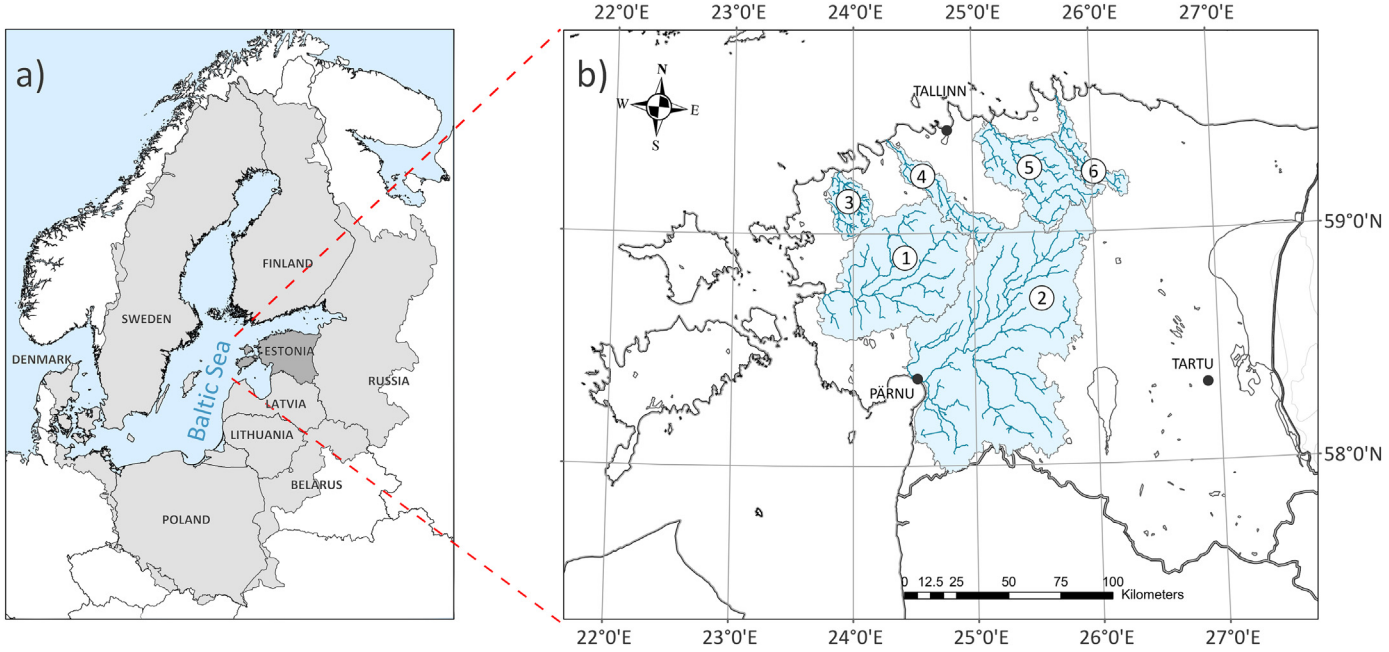

Fig. 1. Geographical location of the Baltic Sea drainage basin (a) and the location of the study West-Estonian basin district (b) in Estonia (1-Kasari, 2-Pärnu, 3-Vihterpalu, 4-Keila, 5-Jägala and 6-Valgejõgi).

Table 1
Characteristics of land-use change scenarios in the study basins.

Basin	Scenario	Forest (mature)	Forest (young)	Cropland	Grassland	Orchard	Water	Urban	Wetlands
Jägala (Kehra) 903 km^2	L0 (km^2)	396.1	91.6	214.6	59.9	9.9	24.6	21.1	85.1
	L1 (change in %)	−29.0	77.1	22.8	−32.6	43.0	–	51.3	–
	L2 (change in %)	1.4	110.9	−51.2	−20.1	43.0	–	51.3	–
Kasari (Kasari) 3213 km^2	L0 (km^2)	1314.1	311.6	817.4	217.3	34.6	95.8	61.2	339.5
	L1 (change in %)	−26.3	83.3	15.0	−34.4	22.2	–	49.1	–
	L2 (change in %)	3.6	117.3	−49.8	−20.1	22.2	–	49.1	–
Keila (Keila) 635 km^2	L0 (km^2)	204.8	46.4	206.3	63.1	20.4	15.0	22.3	56.7
	L1 (change in %)	−26.1	52.3	16.0	−42.8	30.3	–	76.9	–
	L2 (change in %)	23.9	111.8	−50.6	−30.9	30.3	–	76.9	–
Pärnu (Oore) 5160 km^2	L0 (km^2)	2135.9	632.4	1257.8	333.7	64.9	180.9	109.6	444.3
	L1 (change in %)	−21.3	18.7	28.9	−30.1	14.1	–	59.0	–
	L2 (change in %)	11.6	46.2	−44.7	−16.0	14.1	–	59.0	–
Pärnu (Tahkuse) 2080 km^2	L0 (km^2)	827.9	235.6	646.9	117.5	23.0	64.9	45.1	119.1
	L1 (change in %)	−25.2	33.3	20.9	−33.3	27.2	–	62.6	–
	L2 (change in %)	12.2	67.2	−43.1	−12.3	27.2	–	62.6	–
Valgejõgi (Vanaküla) 404 km^2	L0 (km^2)	180.4	39.3	85.6	29.9	3.9	7.0	11.8	46.1
	L1 (change in %)	−15.9	26.1	22.5	−30.7	48.3	–	54.1	–
	L2 (change in %)	11.9	58.0	−54.8	−18.7	48.3	–	54.1	–
Vihterpalu (Vihterpalu) 474 km^2	L0 (km^2)	231.8	51.6	51.4	20.0	2.2	13.5	6.1	97.4
	L1 (change in %)	−25.5	99.1	18.8	−26.7	34.2	–	51.4	–
	L2 (change in %)	−12.5	112.0	−57.3	−14.9	34.2	–	51.4	–

model. Modelling results from the EURO-CORDEX project (Jacob et al., 2014) are used as a SWAT model input for future climate. EURO-CORDEX is an international climate downscaling initiative that aims to provide high-resolution climate scenarios for the whole Europe.

Within the EURO-CORDEX project, models are being run with two resolutions: 50 and 12 km, and both cover the Baltic Sea region and thus, the study area. For the current study, two different RCMs from EURO-CORDEX high-resolution simulations are used: (a) RACMO (Regional Atmospheric Climate Model) climate model with the boundaries from EC-EARTH.

r1i1p1 developed by the Regional Climate Division of KNMI (KNMI) (Van Meijgaard et al., 2008); (b) HIRHAM5 (High-Resolution Limited-Area Model) regional climate model with the boundaries from EC-EARTH r3i1p1 run by the Danish Meteorological Institute (DMI) (Christensen et al., 2007). RCMs applied in this study follow from the analysis done by the Estonian Environment Agency (Luhamaa et al., 2014). Both RCMs contain projections for the historical period (1971–2000) and for the future period (2071–2100), which were used in the current study. To achieve a better comparison with the historical data, RCM data was applied only to existing meteorological stations.

Both future projections are forced by RCP4.5 (Representative Concentration Pathway 4.5) which can be considered as a stabilization scenario in which total radiative forcing is almost stabilized by the end of the 21th century (Clarke et al., 2007; Smith and Wigley, 2006). RCP4.5 assumes relatively ambitious emissions reductions and should be considered “optimistic”. It should be kept in mind that climate change scenarios can be interpreted as plausible descriptions of possible future climatic conditions.

Although RCMs give added value over the more coarse GCMs, dynamical downscaling may not be able to notably improve the simulation skills of those simulated by the GCMs (Rockel et al., 2008). Thus, dynamically downscaled climate may still produce biases among the

downscaled climate which are inherited from the GCM, and carried to the future impact predictions. Despite this finding, RCMs still provide a better description of local climatic conditions. In order to use these RCMs in impact studies, they should be bias corrected. Air temperature (daily minimum and maximum) is modified with the well-known delta method, by monthly additive correction. For precipitation, the local intensity scaling method (LOCI) (Schmidli et al., 2006; Widmann et al., 2003) is used. A more detailed description of the bias correction and its overall performance for the study basins is described in a previous work (Tamm et al., 2015).

3.3. Compilation of land use scenarios

Land use changes are driven by various factors (e.g., population change and economic development). It is recognized worldwide that the arable land areas per capita will be decreasing during next decades (FAO, 2002; FAO, 2009). At the same time the abandonment of agricultural land has occurred (Leal Filho et al., 2016). The main trend in Estonian land use change during the 20th century has been the decrease in agricultural land from 65% in 1918 to 30% in 1994 and the increase of forest cover from 21% to 43%, respectively (Mander and Palang, 1999). Thus, conversions between forest and agricultural land have been the main contributors to land use change. In current study, three land use scenarios were developed for the compilation of the land use maps for the SWAT modelling. The procedures of generating the land use change maps are summarized in a flow chart (Fig. 2).

Firstly, during the land use scenario compilation, it was assumed that wetlands and protected areas will not change, because of their natural character. Secondly, future urbanization is related on the local master plans, i.e. areas reserved for staged urban development are used for urban growth modelling. Thirdly, a forest growth model was applied. The stand diameter of 6 cm at breast height (DBH) was used as a criteria for the division of forest areas into young and old. For the prediction of future forest coverage age class, maturity age from the national law (Forest Act, Rules of Forest Management) was used to determine the harvesting time, i.e., when the forest type changes from old to young. Storylines for three land use scenarios were generated. The first land use scenario is the *Baseline scenario* (L0), which takes the assumption that the land use will remain unchanged during the 21th century and it will be the basis for the two other scenarios (Table 1).

The *Deforestation scenario* (L1) takes the assumption that the dominating global trend will be the increase of agricultural land and land-use intensification due to the growing global demand on food and biofuel (Alexandratos and Bruinsma, 2012; Tilman et al., 2011). Agricultural land use coverage in 1990, at the end of the Soviet era characterized by extensive agriculture was chosen to represent high share of agricultural land. According to Palang et al. (1999) 14310 km2 of area was used for agriculture in this year. Due to political reasons, this number is inflated and the realistic figure was somewhat lower (Palang et al., 1999). Thus, 10% was reduced from this number, resulting an area of roughly 13,000 km^2 which will be used as a criteria to be reached by the end of the 21th century. This scenario predicts an overall increase of agricultural land around 30%, compared to the baseline scenario.

In the *Afforestation scenario* (L2), it is hypothesized that agricultural sector will produce food predominantly for the Estonian domestic market. It is estimated that between 0.15 and 1.1 ha of land is needed to feed a person in a year, depending on the diet (Peters et al., 2016). Estimated figure of 0.5 ha per person was multiplied with the projected population size of 1 million persons with the projected population size of 1 million persons (United Nations, 2013) by the end of the 21th century, yielding an area of 5000 km2 which is needed for intensive agriculture in Estonia. Thus, in this scenario, agricultural land will decrease around 50%, compared to the baseline scenario, predicting a more forested Estonia.

The entire map of Estonia was divided into grid cells with a spatial resolution of 100 m.

Complex Value Index (CVI) was calculated for each cell taking into account a number of different parameters (e.g. soil fertility, area of a plot, shape, distance from a city, etc.) (Maasikamäe et al., 2014). The CVI can be considered as a quality index of a cell, the higher the CVI value, the less susceptible to change. Next, a new cell from the grid was randomly selected for evaluation. The CVI value was compared to a random number from 0 to 1, to evaluate the transition probability. If the CVI of a cell was lower than the random number and the change was logical according to the storyline (e.g. from agricultural land to forest), the transition was accepted. This procedure was looped until a target value corresponding to the storyline. The outcome of the land use modelling was a static map, according to the storyline. The baseline map was replaced by the generated map to carry out hydrological modelling with SWAT.

3.4. Climate and land use scenario combinations

In order to assess the impacts of climate and land use change on runoff, eight scenario combinations (Table 2) were established. Scenarios 1 and 2 only takes into account the change in the land use and can be considered as deforestation and afforestation scenarios, respectively. In Scenario 3 and Scenario 6, the land use remained constant (baseline) while the regional climate models KNMI (C1) and DMI (C2) projections were applied for the period 2071–2100, respectively. The rest of the four remaining scenarios used a combination of both, future climate and land use. Linking climate change models and land use can result in a more realistic scenario for future impact study.

4. Results

4.1. Calibration and validation of the SWAT model for runoff

The initial SWAT model consists of default parameter values, which in order to achieve the best model fit between simulated and measured daily discharge data, need to be calibrated.

For this, eighteen parameters were selected based on various research papers dealing with sensitivity analysis and calibration studies. The selected initial and fitted parameter ranges over all the study basins are reported in Table 3. The calibrated parameter set was transferred back to ArcSWAT by updating the .mdb databases, with SQL sentences. HRU analysis was rerun, after what the SWAT input files were rewritten and the model rerun. The highest attention in creating the model set-up was paid to snow processes. The extent of snowmelt and its timing is crucial in achieving a representative model of the study basins hydrology.

The SWAT model “goodness” of a fit (quantitative) between the daily observed and simulated runoff during the calibration and validation period is presented in Table 4. Authors would like to note, that objective function used with the SUFI2 algorithm for automatic calibration was the KGE. The advantage of using the KGE for calibration is the fact that NSE is sensitive to errors in extreme values and less sensitive to errors in overall distribution, compared to the KGE (Gupta et al., 2009). All of the study basins have a good agreement between the observed and simulated runoff. The average PBIAS for all the study basins for calibration was just around 0.8%, showing quite a small bias towards underestimation. Validation showed similar magnitude of underestimation. It can be said, that no significant model over- or underestimation was found, all the values were in the proposed acceptable range of 10%. Relatively small fluctuations in PBIAS values imply that the water balance is modelled adequately, which is one of the recommendations for a future impact evaluation.

As can be seen in Fig. 2, the SWAT model underestimated some of the peak flows during the calibration and validation period. This can be partly explained by the spatial variability of precipitation, i.e. rainfall may fall more or less intensely at the location of the rain gauges,

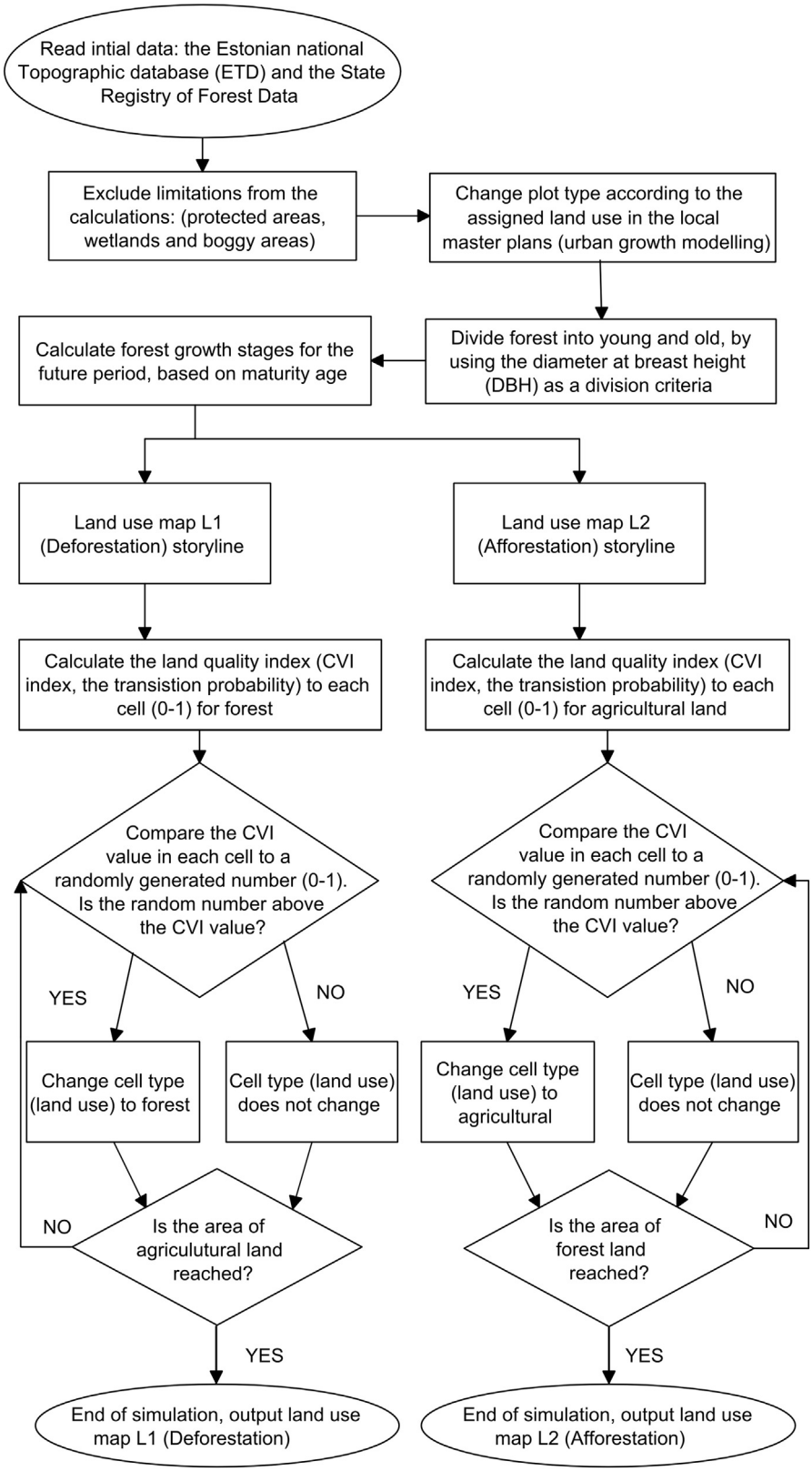
Read intial data: the Estonian national Topographic database (ETD) and the State Registry of Forest Data
Exclude limitations from the calculations: (protected areas, wetlands and boggy areas)
Change plot type according to the assigned land use in the local master plans (urban growth modelling)
Divide forest into young and old, by using the diameter at breast height (DBH) as a division criteria
Calculate forest growth stages for the future period, based on maturity age
Land use map L1 (Deforestation) storyline
Land use map L2 (Afforestation) storyline
Calculate the land quality index (CVI index, the transistion probability) to each cell (0-1) for forest
Calculate the land quality index (CVI index, the transistion probability) to each cell (0-1) for agricultural land
Compare the CVI value in each cell to a randomly generated number (0-1). Is the random number above the CVI value?
Compare the CVI value in each cell to a randomly generated number (0-1). Is the random number above the CVI value?
YES
NO
YES
NO
Change cell type (land use) to forest
Cell type (land use) does not change
Change cell type (land use) to agricultural
Cell type (land use) does not change
NO
Is the area of agriculutural land reached?
Is the area of forest land reached?
NO
YES
YES
End of simulation, output land use map L1 (Deforestation)
End of simulation, output land use map L2 (Afforestation)

Fig. 2. Flow chart for the implementation of the land use change model.

introducing uncertainty in the total estimate of precipitation and thus, in the model calibration. NSE and KGE quantitative statistics indicate a "good" to "very good" performance (Moriasi et al., 2007) for both periods (Table 3). Thus, these modelling results give confidence in the representativeness on the water balance of the study basins. Considering the long period of time (41 years) used for calibration and validation, the SWAT model demonstrated more than satisfactory performance.

Table 2
Summary of generated model scenarios (C0 accounts for baseline climate; C1 accounts for KNMI RCM; C2 accounts for DMI RCM; L0 accounts for baseline land use; L1 accounts for deforestation scenario; L2 accounts for afforestation scenario).

Scenario	Climate	Land use
1	C0 1971–2000	L1 2071–2100
2		L2 2071–2100
3	C1 2071–2100	L0 1971–2000
4		L1 2071–2100
5		L2 2071–2100
6	C2 2071–2100	L0 1971–2000
7		L1 2071–2100
8		L2 2071–2100

4.2. Land use change impact on runoff regime (Scenarios 1 and 2)

The land use change scenario maps L1 and L2 (Fig. 4) were inserted into the calibrated SWAT model to simulate deforestation and afforestation effect on river runoff. In the land use scenario L1, deforestation is driven by the demand for additional agricultural land, leading to an average estimated increase in agricultural land of roughly 20%. Afforestation scenario L2 shows an average forest land cover increase of 25%. Urban areas are predicted to expand significantly (around 50%) in the future, whereas both land use scenarios predict the decrease of grassland (Table 1).

According to Scenario 1, possible changes on runoff are relatively small, annual average flow is expected to raise around 1.3% (Fig. 5). The median flow is expected to increase in the second half of the year up to 4%. In the first half of the year, the effect of deforestation on river flow is almost non-existent. As can be seen from Table 1, the reason of the small change is the fact, that deforestation is relatively small with an average of −8.8%, whereas the scale of afforestation is significantly larger (up to 40%).

Scenario 2 can be described as an afforestation scenario. Projected average increase in forest is around 25%. The effect of afforestation in river flow is more pronounced than in deforestation. This is especially true for the Keila river basin, where the baseline forest cover is slightly below 40%, but increases significantly to 55% (Table 1). The increase in forest land cover can decrease average yearly river runoff over 7% (Keila river), whereas the average change over all basins is around −4.5%. Thus, afforestation extent is larger than deforestation and affects river runoff more, with current generated land use maps. Furthermore, according to Fig. 3, the magnitude of deforestation is marginal, it is not further analyzed in Scenarios 4 and 7 (the combined effect of deforestation and climate change).

Table 4
Calibration and validation results for the north-eastern Baltic Sea study region.

River - Station	Calibration (1970–1997)			Validation (1998–2010)		
	NSE	KGE	PBIAS	NSE	KGE	PBIAS
Kasari - Kasari	0.73	0.79	5.4%	0.70	0.81	−2.3%
Pärnu - Oore	0.80	0.90	−0.7%	0.75	0.87	2.6%
Pärnu - Tahkuse	0.76	0.86	2.9%	0.71	0.80	8.7%
Vihterpalu - Vihterpalu	0.77	0.86	2.4%	0.74	0.86	−3.6%
Keila - Keila	0.74	0.86	1.5%	0.73	0.85	−2.7%
Jägala - Kehra	0.79	0.89	−4.4%	0.74	0.86	1.8%
Valgejõgi - Vanaküla	0.77	0.89	−1.5%	0.71	0.85	4.3%
Average	0.77	0.86	0.8%	0.73	0.84	1.2%

The effect of deforestation and afforestation on yearly river flow is shown on Fig. 6. The effect on forest change on runoff can be generalized as follows: 5% forest change causes a 1% change in runoff. As can be seen from the figure, there is a strong linear trend between these two parameters ($R^2 = 0.97$).

4.3. Climate change impact (Scenarios 3 and 6)

Besides land use, climate is expected to change in the future period as well. In order to assess the sole impact of climate change on river flow, two scenarios are generated. Scenarios 3 and 6, which represent regional climate model projections from KNMI and DMI, respectively. Changes in stream flow due to climate change (DMI and KNMI RCMs) are illustrated in Fig. 7, which describes the average possible changes for the period 2071–2100. According to the KNMI and DMI model, yearly flow is expected to increase among all the study basins around 10% and 26%, respectively. Both climate models predict a significant decrease in April (40–50%), when typical yearly peak flow occurs from snowmelt. The third major similarity among scenarios is the increase of the winter flow of around 50–70%. Significant differences in the

Table 3
Summary of the parameters used for calibration and the fitted ranges over all the study basins.

Process	Parameter [a]	Description and units	Initial parameter range	Fitted parameter range over all the study basins
Groundwater	v_GW_DELAY.gw	Groundwater delay time (days)	0.5 … 4.0	1.31 … 2.19
	v_ALPHA_BF.gw	Base flow alpha factor (days)	0.05 … 0.25	0.10 … 0.18
	v_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.01 … 15.0	2.38 … 7.75
	v_GW_REVAP.gw	Groundwater “revap” coefficient	0.02 … 0.20	0.07 … 0.10
	v_REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm)	0.1 … 15	9.05 … 14.55
Surface	r_CN2.mgt	Initial SCS runoff curve number for moisture condition II	−0.15 … 0.15	−0.05 … 0.18
	v_SURLAG.bsn	Surface runoff lag coefficient	0.05 … 0.15	0.06 … 0.13
	v_OV_N.hru	Manning's “n” value for overland flow	0.1 … 0.4	0.14 … 0.32
	v_CH_N2.rte	Manning's “n” value for the main channel	0.02 … 0.1	0.03 … 0.05
	v_EPCO.hru	Plant uptake compensation factor	0.5 … 1.0	0.37 … 0.72
	v_ESCO.hru	Soil evaporation compensation factor	0.5 … 1.0	0.74 … 0.98
Soil	r_SOL_AWC.sol	Available water capacity of the soil layer (mm H_2O/mm soil)	−0.2 … 0.2	−0.32 … 0.42
	r_SOL_K.sol	Saturated hydraulic conductivity (mm/h)	−0.2 … 0.2	−0.05 … 0.38
	r_SOL_BD.sol	Moist bulk density (mg/m^3)	−0.2 … 0.2	−0.19 … 0.16
Snow	v_SFTMP.bsn	Snowfall temperature (°C)	−1.5 … 1.5	−1.4 … -0.50
	v_SMTMP.bsn	Snowmelt temperature (°C)	0.0 … 2.0	0.11 … 0.85
	v_SNOCOVMX.bsn	Minimum snow water content that corresponds to 100% snow cover (mm H2O)	40 … 80	43.9 … 76.5
	v_SNO50COV.bsn	Fraction of SNOCOVMX that corresponds to 50% snow cover	0.4 … 0.7	0.44 … 0.64

[a] r_: parameter value is multiplied by (1 + a given value) or relative change; v_: parameter value is replaced by given value or absolute change.

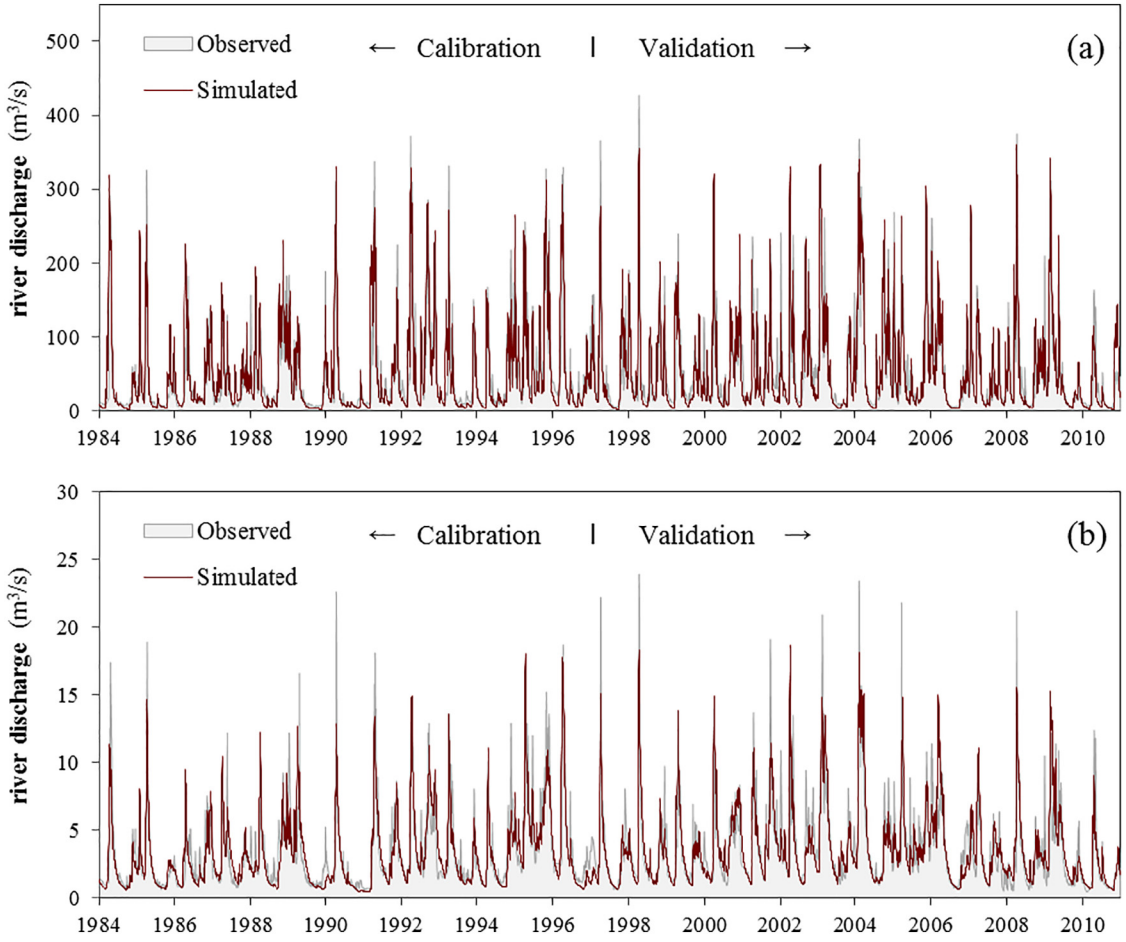

Fig. 3. Observed and simulated daily runoff hydrograph at (a) Pärnu river [Oore], (b) Valgejõgi [Vanaküla] in the period 1984–2010.

summer and autumn runoff are evident between Scenarios 3 and 6. Scenario 3 (KNMI) predicts a decrease in runoff for summer and autumn months whereas Scenarios 6 (DMI) reveals a significant increase of runoff around 40–80%. Thus, the signals from both climate models are unclear during this period and add uncertainties to future climate interpretations.

4.4. Combined impact of land use and climate change (Scenarios 5 and 8)

Under the combined impact of climate and land use change, the average annual runoff of the study basins is expected to increase in the future. The effect of deforestation (Scenarios 4 and 7) was not further investigated, because of its marginal impact on runoff. When climate change was considered together with land use change (afforestation), the latter impact on runoff was not so pronounced, compared to climate change. The effect of afforestation was an average reduction of annual runoff by 5% over all study basins. Whereas, the effect of climate change was an annual increase of 10% to 33%, with KNMI and DMI climate model projections, respectively. It is interesting to note that the monthly interquartile range of runoff change in Scenario 5 and 8 clearly narrows, when the generated deforestation map L2 is applied with climate models (Fig. 8). This is especially true for Scenario 8, where the modelled monthly runoff impact "difference" between study basins on winter and spring flows is small (< 10%). Possible changes in the future runoff for the summer and autumn months are unclear. While Scenario 5 shows a decrease (around 20%), whereas Scenario 8 predicts a large increase (around 50%). These differences are inherited from the climate change scenarios, the impact of afforestation is secondary.

5. Discussion

The integration of land use change and climate change models with a hydrological model like SWAT, can improve the efficiency of predicting the hydrologic response. Using a combination of both models gives a more realistic description of the processes taking place in the system. The hydrological model gave some answers on the relative importance of land use versus climate change effect on river runoff.

Snow-melt dominated regions in North-Europe are expected to receive more runoff during winter and less is the spring months (Arheimer and Lindström, 2015; Donnelly et al., 2017). These findings are consistent with the current study. The climate change effect on spring runoff is evident, compared with the land use change, where its impact is marginal. This is because the projected increase in temperature, which translates to a shorter snow season and less snow accumulation in winter. However, there is no clear agreement among the climate scenarios, how the autumn runoff will be affected in the study area (Fig. 5).

Different climate change studies analyze certain aspects of the nature, by using different input data quality, methods and assumptions, hindering the straightforward comparison of the results between studies. Karlsson et al. (2016) evaluated the sensitivity of the results to the choice of hydrological model. Although hydrological models showed similar performance during calibration, the mean discharge response to climate change may vary significantly (up to 30% among the used hydrological models). Even with such variations, they found that the choice of the climate model was the dominant factor influencing the mean discharge at the end of the century.

Piniewski et al. (2017) evaluated the robustness (Knutti and

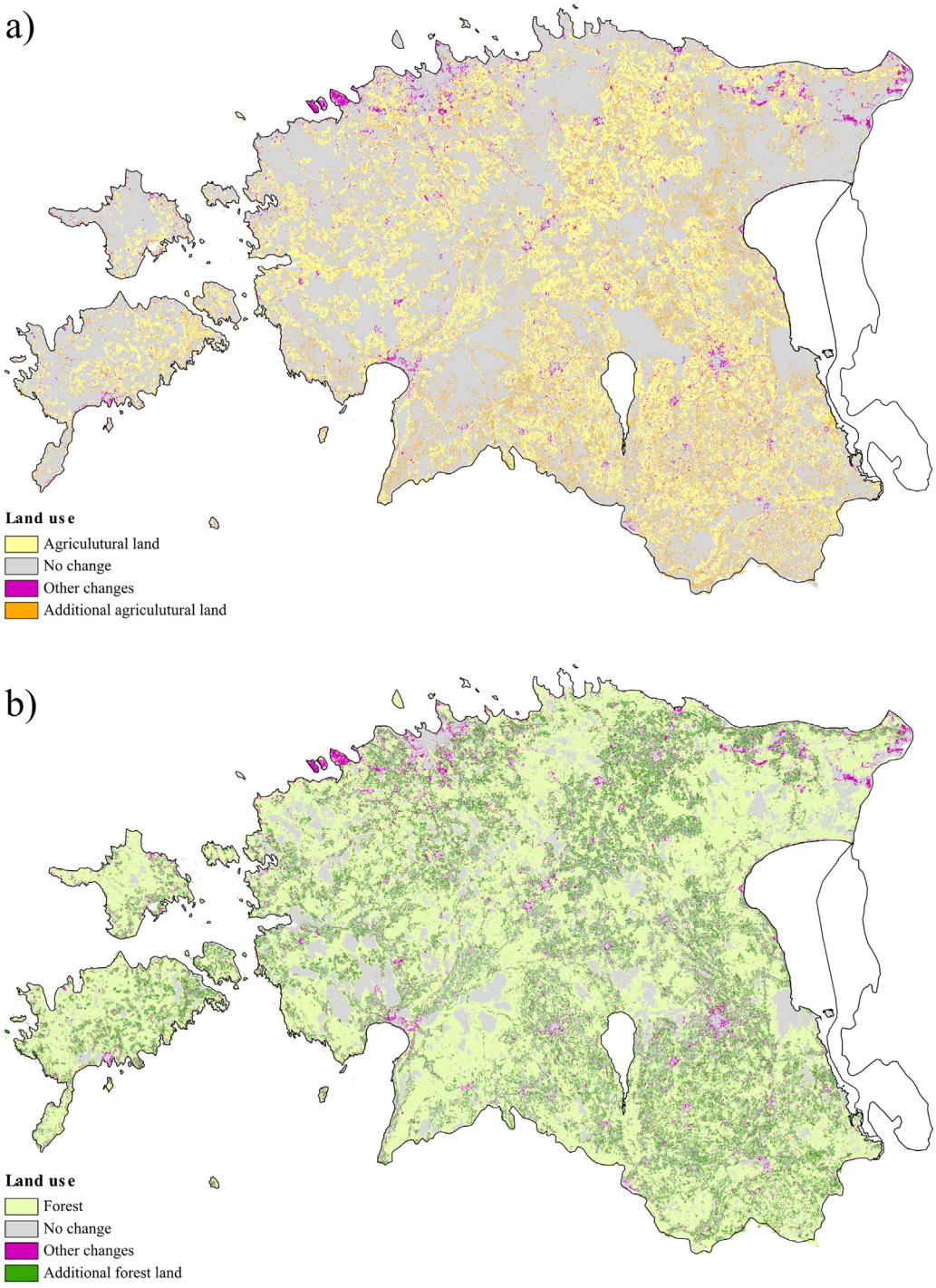

Fig. 4. Spatial pattern changes in land use between the baseline (1971–2000) and the future period (2071–2100) under (a) the deforestation and (b) the afforestation land use scenario.

Sedláček, 2013) of the climate change signal in an ensemble of nine bias-corrected EURO-CORDEX simulations over two large basins in Poland, which drain to the Baltic Sea. They found that although the investigated climate models agree on the sign of precipitation change, annual total precipitation projections are not robust (low signal-to-noise ratio). Depending on the climate model used, the change in seasonal precipitation can vary greatly. It can be generalized from their study that seasonal precipitation in the RCP 4.5 scenario shows more robustness than the RCP 8.5. Jacob et al. (2014) showed that future changes among an ensemble of EURO-CORDEX simulations for mean annual temperature are significant and robust in the same Eastern Europe region. Thus, although using only two RsCM's, KNMI and DMI forced by a RCP 4.5, the uncertainty in the interpretation of results increases.

The land use representation in a hydrological model can be either static or dynamic. In current study, a static “averaged” land use map is used for the whole baseline period of 30 years. This is mainly because the lack of dynamic maps for this period. In order to achieve a better comparison basis with the future, static “averaged” land use change scenario maps L1 and L2 were implemented to SWAT. Wagner et al. (2017) found that using a static map approach provides a relatively good approximation of the hydrological impacts if a linear land use

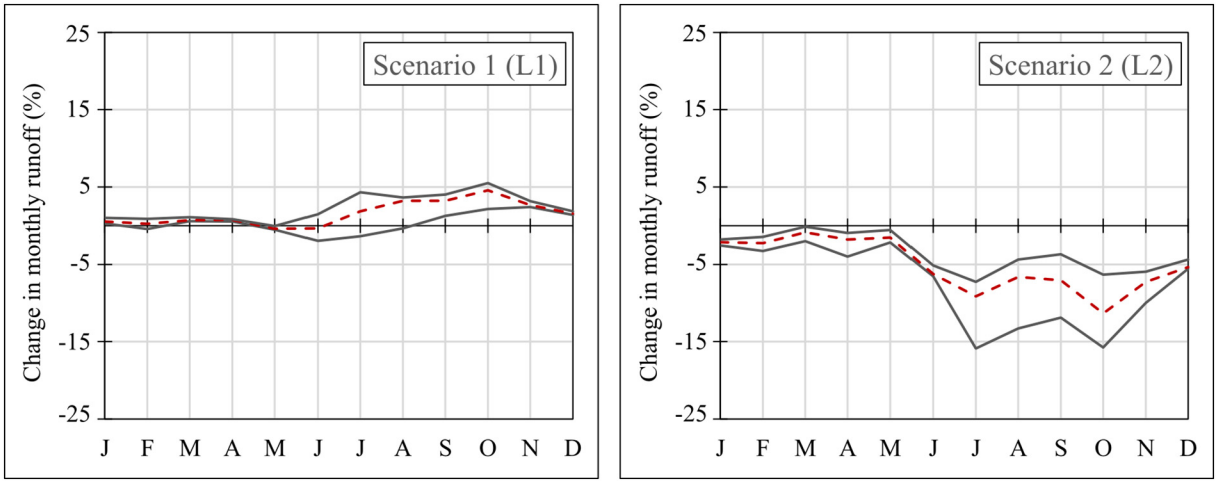

Fig. 5. The effect of deforestation (Scenario 1) and afforestation (Scenario 2) on river monthly flow among the study basins (dashed is the median modelled change, solid lines represent the interquartile range).

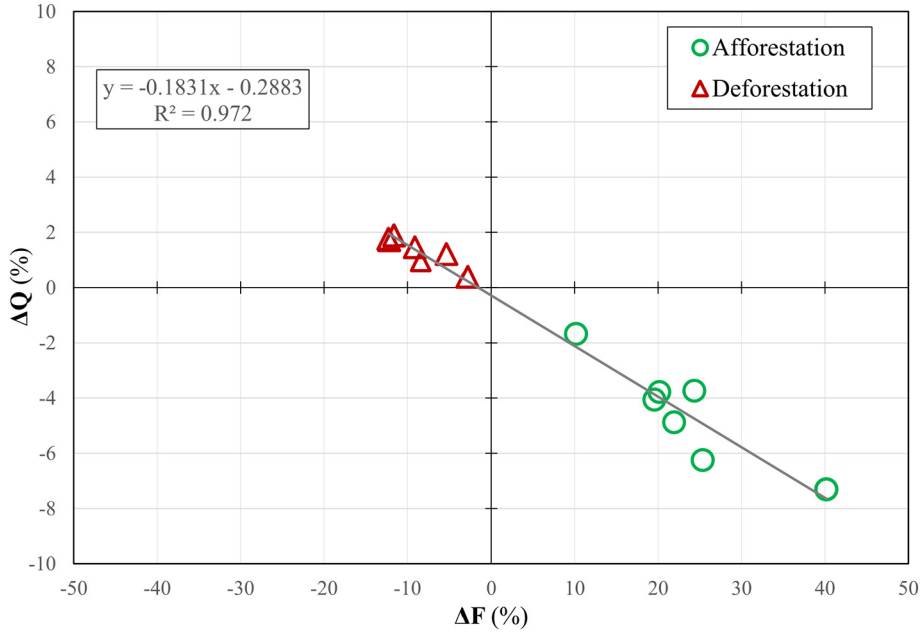

Fig. 6. The relationship between forest (ΔF) cover- and annual runoff (ΔQ) change in the study basins.

change is assumed. However, in the Baltics, land use changes have been driven by political decisions, i.e. such rapid changes are unpredictable. Thus, a linear development of land use changes is assumed. However, the importance of a dynamic representation of land use changes should not be neglected (Castillo et al., 2014; Wagner and Waske, 2016).

The magnitude of the land use change impact on runoff varies. Theoretically, increase in the forest cover will lead to higher water-holding capacity of the basin area, and vice versa. Deforestation effect on runoff was analyzed in a small (97 km^2) Slovakian basin (Hlásny et al., 2015). The deforestation induced an increase in the total runoff by 20.4%. Tong et al. (2012) found that the effect of land use on runoff can be as significant as climate change (mean daily flow increased 29.1%). In the current study, a 5% forest increase causes around a 1% reduction in annual runoff, revealing a strong linear trend. Changes in annual runoff were more affected in the case of increasing forested land (L2) and during the warm period, whereas deforestation (L1) and during the cold period, the effect is comparably weak.

Zhang et al. (2016) compared the sensitivities of annual runoff to forest cover change in large (≥1000km^2) and small (< 1000km^2) basins. The hydrological regime was found to be less influential factor in small basins than in large ones. Out of the seven basins used in this study, three can be considered large and four can be categorized as small, however no notable importance on the basin scale was detected.

These results emphasize the importance to apply climate change models with land use. Climate change still seems to be the driving force in the possible changes in runoff regime. However, land use change scenarios should not be discarded from future impact studies. This study did not cover the possible impact on water quality, which is probably more affected by the land use change, compared to quantity (Dimitriou and Mentzafou, 2016; Trang et al., 2017).

6. Conclusion

In this study, the SWAT model was applied to assess the potential impact of future climate change and land use change on river runoff in the north-eastern Baltic Sea region. The model was calibrated and validated for the period of 41 years. The SWAT model demonstrated more than satisfactory performance. The calibrated SWAT model was used as

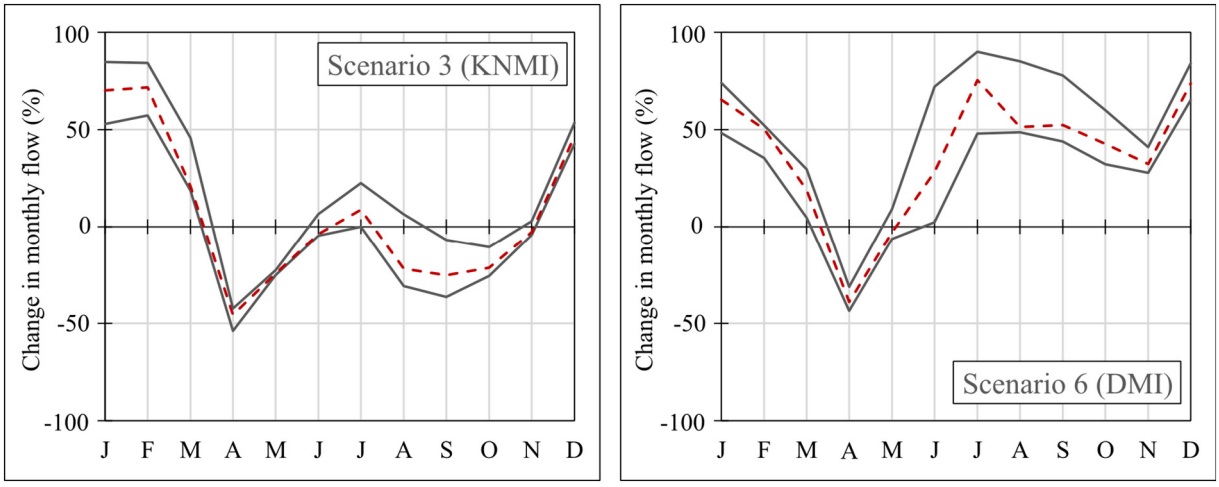

Fig. 7. The effect of climate change Scenario 3 (KNMI RCM) and Scenario 6 (DMI RCM) on river monthly flow among the study basins (dashed is the median change, solid lines present the interquartile range).

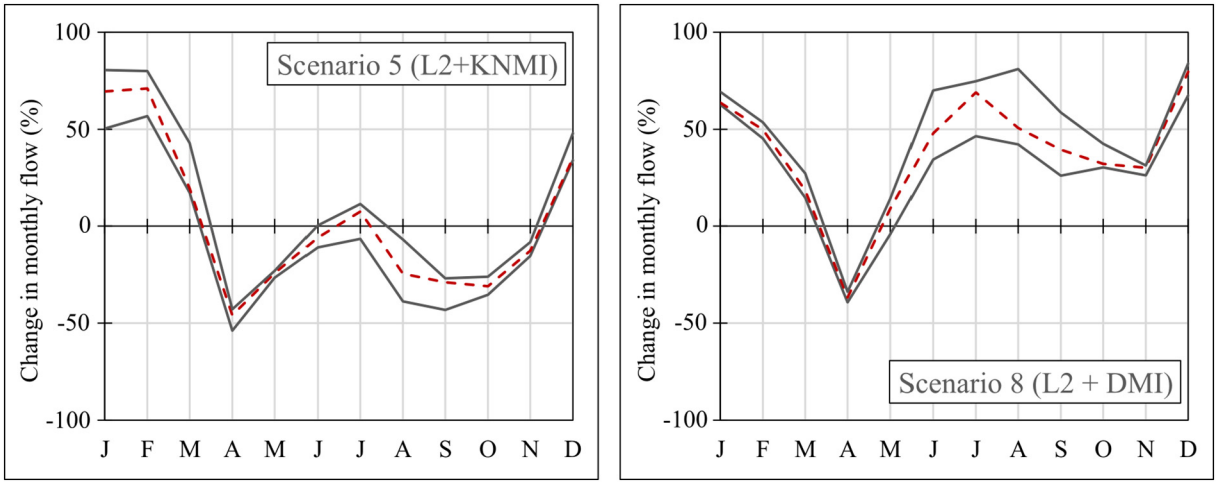

Fig. 8. The effect of climate and land use change Scenario 5 (KNMI RCM and afforestation) and Scenario 8 (DMI RCM and afforestation) on river monthly flow among the study basins (dashed is the median change, solid lines present the interquartile range).

a tool to estimate possible water resource changes in the future. For this, two hypothetical (but plausible) land use change maps were generated and two climate change model projections were used. From these maps and models, different scenarios were generated and assessed. According to the results, annual average flow is expected to increase by the end of the century, compared to the baseline period. There is a strong agreement among RCMs for winter and spring, where notable changes were found. However, the magnitude of the change (during the summer and autumn period) varies greatly among the climate change scenarios.

The principal finding of this study is the strong linear correlation between forest cover change and river flow change. It can be generalized to the study region, a 5% forest cover reduction causes a 1% increase in annual runoff. Secondly, land use change impact on runoff is important on an annual scale, in the study region. However it was found that changes in land use does not alter the monthly runoff variation as significantly as climate change. Thirdly, the combined effect of land use and climate change was found to be non-additive in the study.

In general, findings from the would be beneficial to policy makers as it contributes to a deeper understanding of natural and man-made processes, to develop long term strategies in forest management and to harness the positive impacts of overall increase (e.g. increased hydropower potential) in the north-eastern Baltic Sea region river runoff.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.catena.2018.04.029. These data include the Google map of the most important areas described in this article.

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